

Hadronic molecules: meson-baryon hybrids

M.Shmatikov *

Institut für Theoretische Physik

Ruhr Universität Bochum, D-44780 Bochum, Germany

e-mail: michaels@hadron.tp2.ruhr-uni-bochum.de

Abstract

The existence of hadronic molecular-type hybrids consisting of a baryon and a meson is argued. Long-range interactions due to one-pion exchange are shown to be strong enough to produce a loosely bound state. Specific features of a molecular hybrid are discussed.

Typeset using REVTeX

*Permanent address: Russian Research Center "Kurchatov Institute", 123182 Moscow, Russia

The advent of QCD made customary classification of hadrons in terms of their quark content, ordinary baryons and mesons being qqq and $\bar{q}q$ states respectively. Considerable efforts, pioneered by Jaffe [1], have been spent to explore the possible existence of more complicated states containing four or more quarks. Investigations in the framework of the naive quark model [2,3] have shown that some mesonic states may have a predominantly molecular structure in the form of loosely bound $\bar{K}K$ pairs. It should be noted that this conclusion was obtained by means of an analysis of forces operating in the QCD realm i.e. in terms of quark-gluon forces. Quite different mechanism for generating multiquark deuteron-like states was suggested by Törnqvist [4,5]. Guided by the fact that it is possible to get the bound state of two nucleons by one-pion exchange only (strictly speaking, the tensor part of the latter), he argued existence of (loosely) bound states involving either two vector mesons or a vector-meson and a pseudoscalar-meson. Indeed, the results he obtained are rather encouraging since the one-pion exchange mechanism was shown to be strong enough to bind heavy (D^- and B^-) mesons [5]. However, for lighter mesons containing K , K^* and vector ρ , ω mesons one-pion exchange can provide about only half of the attraction required for the emergence of a bound state. Since binding energy is a result of an interplay between an attracting potential and a kinetic energy of coupling particles, a requirement to be satisfied in the formation of a shallow bound state for some simple-type potentials can be formulated in terms of a scaling condition relating the strength constant of the potential and the masses of the particles [6]. Such a scaling condition was addressed in [7] with emphasis on the Yukawa potential representing the central part of the one-pion exchange interaction. Since the coupling constants of the π -meson to hadrons is known, the scaling condition allows to introduce the notion of a critical mass, i.e. the minimal reduced mass of the components required for the molecule formation [7]. The boundedness condition is apparently satisfied for infinitely heavy mesons. Manohar and Wise analyzed a system involving two heavy and two light mesons (more precisely the $QQ\bar{q}q$ system) to show that the one-pion exchange provides an attraction strong enough to bind two mesons containing b -quarks [8].

All the molecular states considered in the papers cited above referred to mesons (a system containing the vector K^* meson and a Σ^- (or Ξ^-) hyperon was analyzed in [7] with the negative conclusion as to possible emergence of a bound state). We consider a more 'exotic' system involving a heavy meson and a nucleon. If bound, it will manifest itself as a baryon with the same flavor as the heavy quark. Provided the binding energy is large enough, it will be subject to weak decay only.

The choice of the components of a 'molecule-to-be' is dictated by several requirements. The state-of-the-art understanding of nonperturbative QCD mechanisms does not give any hope for obtaining more or less reliable quantitative results. Thus we are bound to consider a long-range force whose characteristics are known (or can be extracted) from experiment, i.e. the celebrated one-pion exchange. Pion-exchange being established as a driving force, the choice of components becomes more selective. First, the π -meson is known to couple to the isospin 'charge' of a particle. Then the nucleon containing 3 light (u - and d -) quarks is singled out among other (stable) baryons. Second, the π -meson does not couple to a pseudoscalar particle, thus prompting the choice of a vector meson as the second component. Finally, the large mass of the latter is anticipated to ensure boundedness with even weak enough pion-mediated forces. Note also that the sign of the π -meson coupling to a (vector) meson depends on its quark content: it will be shown below that attraction occurs between the

nucleon and the heavy vector antimeson (i.e. $(\bar{Q}q)$ state).

The specific properties of the pion almost unambiguously determine the quantum numbers of the meson-nucleon system. Indeed, the pion-induced tensor force at nearly all distances, where the one-pion-exchange is distinguished, is known to be much stronger than its central counterpart [9]. At the same time, the presence of non-zero orbital angular momenta invokes additional repulsion due to the centrifugal barrier. Thus we are urged to conclude that the most favorable situation occurs in the $S - D$ system, just as it happens in the deuteron case. The vector-meson – nucleon system may have two values of the total spin equal to $1/2$ and $3/2$. The former value seems to be more promising. Indeed, the total spin \vec{S} is the sum of spins of the components,

$$\vec{S} = \vec{\Sigma} + \frac{1}{2}\vec{\sigma}, \quad (1)$$

with the spin operators of the vector meson $\vec{\Sigma}$ and the nucleon $\vec{\sigma}$ being normalized as $\vec{\Sigma}^2 = 2$ and $\vec{\sigma}^2 = 3$. The central part of the one-pion-exchange potential is known to be proportional to the scalar product of spins of involved particles. Using (1), it can be cast in the form:

$$\vec{\Sigma}\vec{\sigma} = S(S+1) - \frac{11}{4} \quad (2)$$

One can infer readily from the expression above that the spin scalar product under consideration is twice as large for the doublet case ($S = 1/2$) than for the quartet one ($S = 3/2$). Finally, the strength of the one-pion-exchange potential depends on the isospin of the system. Heavy mesons (like nucleons) belong to an isodoublet and the interaction in the isoscalar state is 3 times stronger than that for the isovector state. Thus we conclude that the most favorable conditions for obtaining a bound molecular-like state of the nucleon and the vector meson take place in the state with the quantum numbers $J^\pi(T) = 1/2^+(0)$. In the $L - S$ basis this state corresponds to the coupled $^2S_{1/2} - ^4D_{1/2}$ waves and as such, bears much similarity to the properties of the deuteron itself.

We proceed now to the quantitative analysis of the considered system and begin with the parameter controlling emergence of a zero-energy bound state for the Yukawa potential [6],

$$s = 0.5953 \cdot 2\bar{m} \gamma \frac{V_0}{m_\pi^2}, \quad (3)$$

where \bar{m} is the reduced mass of interacting particles, m_π is the π -meson mass and V_0 is the potential strength 'unit' introduced in [5]:

$$V_0 = \frac{m_\pi^3}{12\pi} \frac{g^2}{f^2}. \quad (4)$$

The ratio of coupling constants g/f is determined by the effective Lagrangian of (constituent) quark - pion coupling

$$\mathcal{L}_{int} = \frac{g}{f} \bar{q} \gamma^\mu \gamma^5 \vec{\tau} q \partial_\mu \vec{\pi}, \quad (5)$$

where f is the pion decay constant and g has the meaning of an effective pseudovector quark-pion coupling constant. At present we will not specify its numerical value but assume only that it can be extracted either from the constant of the πNN coupling or from the width of the pionic decay of the vector meson into a pseudoscalar one without serious contradictions. The parameter γ in (3) combines spin-isospin factors which depend on the quantum numbers of interacting particles and of the system as a whole.

To make our conclusions more transparent, we compare the s parameter (3) for the (heavy) vector-meson and nucleon system (s_{VN}) to its NN counterpart:

$$\rho \equiv \frac{s_{VN}}{s_{NN}} = \frac{\gamma_{VN}}{\gamma_{NN}} \cdot \frac{2}{1 + m_N/m_V}. \quad (6)$$

Each nucleon furnishes a $5/3$ factor, and in the NN system one more factor 3 emerges in both 1S_0 and $^3S_1 - ^3D_1$ states. At the same time, in the VN system, isospin and spin factors are equal (up to a sign) to 3 and 2 respectively (compare to (2)) yielding

$$\rho = \frac{2 \cdot 5/3 \cdot 3}{(5/3)^2 \cdot 3} \cdot \frac{2}{1 + m_N/m_V}. \quad (7)$$

If, following the arguments of [7], we consider the s_{NN} value as corresponding to the emergence of a bound state with zero energy (strictly speaking, the near-threshold virtual state in the 1S_0 channel), inspection of (7) shows that, for given quantum numbers of the VN state, a bound state will emerge for the mass of the vector meson $m_V \geq 5/7 m_N$. This is a condition which is readily satisfied for B^* and even D^* mesons. The boundedness criterion, as formulated in [6],

$$s_{VN} \geq 1 \quad (8)$$

proves to be more stringent. Indeed, substituting in (7) the known s_{NN} value ($s_{NN} \approx 0.33$), we arrive at the expression

$$s_{VN} \approx \frac{0.784}{1 + m_N/m_V} \quad (9)$$

showing that the condition (8) cannot be satisfied even for an arbitrarily heavy vector meson. Note, however, that the s_{VN} parameter in the case of the B^*N system ($m_{B^*} \approx 5.3$ GeV) proves to be $s_{VN} \approx 0.67$. This value which is twice as large as that of the NN counterpart. It can be concluded that the conditions for binding a heavy meson and a nucleon by the one-pion-exchange forces are very favorable.

We proceed now to the quantitative investigation of the system containing a heavy vector meson and the nucleon. The potential of one-pion exchange operating between these particles reads

$$V_\pi(r) = \frac{5}{3} V_0 \kappa [C_s \cdot \tilde{y}_0(m_\pi \cdot r) + C_t \cdot \tilde{y}_2(m_\pi \cdot r)] . \quad (10)$$

The potential-strength parameter V_0 is defined in (4). The factor κ is the scalar product of the isospin Pauli matrices equal to -3 and 1 in the case of the isoscalar and isovector state

respectively. The matrices C_s and C_t are determined by the values of the spins and orbital momenta. In the case of ${}^2S_{1/2} - {}^4D_{1/2}$ coupled channels they read

$$C_s = \begin{pmatrix} -2 & 0 \\ 0 & 1 \end{pmatrix}; \quad C_t = \begin{pmatrix} 0 & -1 \\ -1 & \sqrt{2} \end{pmatrix} \quad (11)$$

Finally, the $\tilde{y}_{0,2}$ functions in (10) are the well known Yukawa-type functions

$$y_0(x) = \frac{\exp(-x)}{x}; \quad y_2(x) = \frac{\exp(-x)}{x} \left(1 + \frac{3}{x} + \frac{3}{x^2} \right) \quad (12)$$

regularized at small distances. We use the regularization employed in [5], which corresponds to introducing a monopole-type formfactor at each vertex of π -meson coupling. The cut-off parameters Λ in both vertices are assumed to be the same. Before proceeding to the results of computations it would be relevant to stress the different role of heavy vector mesons and antimesons. According to the classification scheme of the Particle Data Group [10] a heavy mesons B has the quark structure as follows: $B = (q\bar{b})$ where q is a light quark. The π -meson couples to a light quark only. The vertices of the π -meson interaction with a particle and an antiparticle differ in sign due to negative G -parity of pion. The strength of interaction of two particles with the isospin 1/2 is 3 times larger in the isoscalar case than in the isovector one. The strongest attraction is therefore achieved in the (isoscalar) $(N\bar{B}^*)$ system, while the one-pion exchange in the NB^* system provides attraction in the isovector state only. This circumstance predetermines the flavor quantum number of the hybrid state under consideration.

Using the potential (10) ¹ we solve the eigenvalue problem to search for a bound-state solution of coupled Schrödinger equations. As a check, we calculate the binding energy of the deuteron and reproduce the experimental result with good accuracy for the values of parameters $V_0 \approx 1.34$ MeV (which corresponds to the value of πNN coupling constant $f_{\pi NN}^2/(4\pi) \approx 0.08$) and the value of the cut-off parameter $\Lambda \approx 1.35$ GeV. Note, that the Λ value (which is actually under debate) exceeds by about 10% that used in computations of [5]. With this set of parameters a bound $(N\bar{B}^*)$ state does not exist. It appears with the increase of the πqq coupling constant g which results in a stronger attraction scaled by the V_0 factor (4). With g coupling constant increased by $\approx 40\%$ the binding energy makes about 1 MeV. The specific value of the binding energy is very sensitive to the details of short-range interaction between components of the molecule-type state. Beyond the one-pion-exchange mechanism in the hierarchy of interaction ranges we need to consider the two-pion exchange. A strong correlation between pions results in an attraction of shorter range, which is usually simulated by the exchange of the scalar-isoscalar σ -meson. The constant of its coupling to the quark can be determined in the framework of the linear σ -model. More precisely, in this model this coupling constant is equal to that of quark pion-coupling, and the latter can be related, owing to the equivalence of pseudoscalar and pseudovector types of coupling, to the g coupling constant in the Lagrangian (5). Taking, rather arbitrarily, the mass of a constituent quark involved in these relations equal to $m_q \approx 1/3 m_N$ and the

¹Note that additional factor (-1) appears in the case of $N\bar{B}^*$ coupling

mass of the σ -meson $m_\sigma \approx 2m_q$ (as prescribed by the chiral-symmetry limit) we get an attractive potential generated by σ -meson exchange. The addition of such a potential, with the strength weakened for exploratory purposes by a factor 0.1, deepens the binding energy to ≈ 10 MeV. The radial dependence of the $^2S_{1/2}$ and $^4D_{1/2}$ components of the wave function is exhibited in fig.1. Characteristic distances r_c , corresponding to the binding energy E_b , are of the order of $r_c \approx 1/\sqrt{2\bar{m}E_b}$, where $\bar{m} \approx 0.8$ GeV is the reduced mass of the NB^* pair. Hence for the case of $E_b \approx 10$ MeV we get $r_c \approx 1.5$ fm. One can see that both components peak at $r \approx 0.5$ fm and fall down rather slowly to about 1.5 fm. Such behavior of the wave functions complies with the long-range character of the one-pion exchange affected by strong attraction of shorter range.

Molecular-type hybrid state is to be expected as well in the system including the nucleon and the D^* -meson. However, the reduced mass of the (ND^*) pair is smaller than that of the (NB^*) pair. Components being more light, emergence of a near-threshold bound states requires stronger attractive potential. Corresponding increase of g coupling constant with respect to the (NB^*) case makes $\approx 10\%$.

A qualitative analysis of the $(N\bar{B}^*)$ system with zero isospin in combination with numerical calculations indicates the existence of a bound state with the $J^\pi = 1/2^+$ quantum numbers. It has the properties of an isoscalar baryon with the flavor of the b -(anti)quark and the mass $m \approx m_N + m_{B^*} \approx 6.2$ GeV. The exact value of the binding energy E_b depends on the details of short range interaction and cannot be calculated without invoking (poorly known) QCD mechanisms operative in the nonperturbative domain. It should be stressed at the same time that the properties of the hybrid $(N\bar{B}^*)$ molecular-type state depend crucially on the E_b value. Indeed, the vector B^* meson, because of small mass difference with its pseudoscalar partner ($\Delta m = m_{B^*} - m_B \approx 46$ MeV [10]), decays through the emission of a γ -quantum. If the binding energy is small, the hybrid state has a very diffuse structure and it would be reasonable to expect that the properties of the \bar{B}^* meson are not significantly affected by the presence of the nucleon. In this case, the decay time of the hybrid molecular state will be about the same as that of a free vector meson. For larger values of E_b the decay will be hindered by the diminished phase space volume and, finally, for $E_b \geq \Delta m$ the hybrid state will be stable with respect to both strong and electromagnetic decays. In any case, its width is expected to be very small, not exceeding the width of the B^* vector meson.

ACKNOWLEDGMENTS

The author is indebted to the members of the Mittelenergiephysik Arbeitsgruppe and especially to Prof.Dr.M.F.Gari and Dr.J.A.Eden for kind hospitality extended to him during the stay at Bochum University.

REFERENCES

- [1] R.L.Jaffe, Phys.Rev. **D15** (1977) 267; ibid. **D17** (1978) 1444.
- [2] J.Weinstein and N.Isgur, Phys.Rev.Lett. **48** (1982) 569;
Phys.Rev. **D27** (1983) 588; Phys.Rev. **D41** (1990) 2236.
- [3] K.Dooley, E.S.Swanson and T.Barnes, Phys.Lett. **B275** (1992) 478.
- [4] N.A.Törnqvist, Phys.Rev.Lett. **67** (1991) 556.
- [5] N.A.Törnqvist, Helsinki preprint HU-SEFT R 1993-12 (1993).
- [6] J.M.Blatt and V.F.Weisskopf, Theoretical nuclear physics
(*Wiley*, New York, 1952).
- [7] T.E.O.Ericson and G.Karl, Phys.Lett. **B309** (1993) 426.
- [8] A.V.Manohar and M.B.Wise, Nucl.Phys. **B399** (1993) 17.
- [9] T.Erikson and W.Weise, Pions and nuclei (*Clarendon*, Oxford, 1988).
- [10] Particle Data Group, Phys.Rev. **D50** (1994) 1173

This figure "fig1-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9501259v1>